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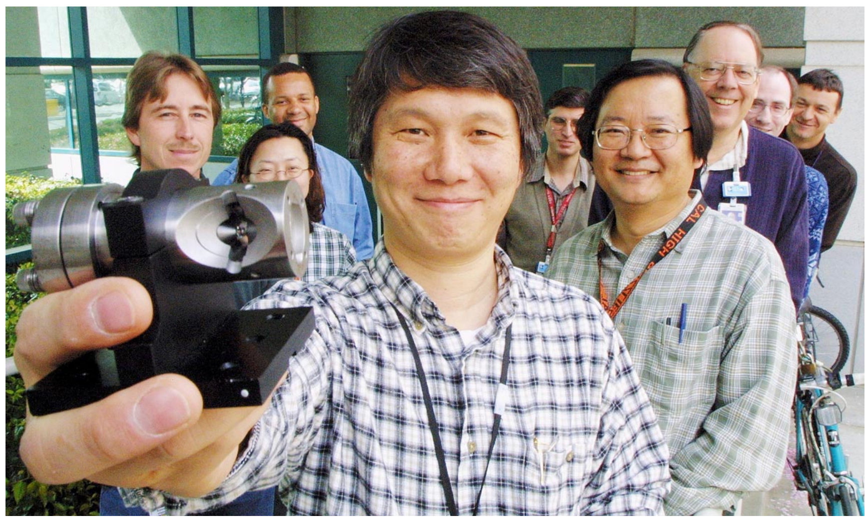
Hyunchae Cynn, High-Pressure Physics Group, Lawrence Livermore National Laboratory, Livermore, California
cynn1@popeye.llnl.gov

Osmium Is Stiffer Than Diamond

H. Cynn[1], J.E. Klepeis[1], C.-S. Yoo[1], D.A. Young[1]

[1]Lawrence Livermore National Laboratory, University of California, Livermore, California

Scientists from the U.S. Department of Energy's Lawrence Livermore National Laboratory (LLNL) working at the NSLS and LLNL's Stanford Synchrotron Radiation Laboratory have reported the surprising discovery that metallic osmium is stiffer than covalently bonded diamond. The researchers also found that iridium and ruthenium are as incompressible as rhenium. In addition, they performed first-principles calculations that independently confirm the observed trend in the transition metal bulk moduli.



Members of the LLNL high-pressure physics experimental group and collaborating theoretical physicists. Physicist Hyunchae Cynn (front), who is the lead author of the study, is holding a diamond-anvil cell of the type used in the osmium experiments.

Diamond is the hardest known material. However, in searching for other hard materials it is generally simpler to study the compressibility, which is often correlated with the hardness. The compressibility is a measure of how much the volume changes for a given change in pressure and is equal to the reciprocal of the bulk modulus. A material that has a low compressibility (incompressible, high bulk modulus) is stiff or difficult to compress.

In addition to being the hardest known material, diamond also held the record for the highest bulk modulus at 443 gigapascals (4.43 million times atmospheric pressure). However, our newly measured value of 462 gigapascals for osmium exceeds that of diamond. We also found that iridium and ruthenium are as incompressible as rhenium, which has previously been reported to be a strong metal.

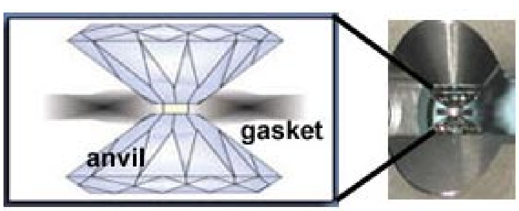


***Figure 1**. Two opposing diamond anvils supported by tungsten carbide mounts provide a sample chamber by placing a metal gasket in between the flat tips (approximately 300 micrometers in diameter) of the two diamond anvils. The gasket has a small hole (less than 100 micrometers) drilled at the center.*

It has long been known on the basis of the simple Friedel model of chemical bonding in transition metals that the largest bulk moduli should occur in the middle of each transition metal row in the periodic table. The position of osmium in the middle of the 5d row is thus consistent with the high value of the bulk modulus we have obtained. As far as we know, no compressibility data for osmium at high pressures have been reported previously.

We performed compression studies with a diamond-anvil cell (**Figure 1**) up to 65 gigapascals for osmium, ruthenium, and iridium. Condensed argon was used as a pressure medium, and ruby grains smaller than three micrometers in diameter were used to determine the pressure. Powder samples with grain sizes less than five micrometers were contained inside a small hole (80 micrometers in diameter) drilled into a rhenium gasket.

The measured diffraction patterns were dispersed either in energy using unfocused white x-rays from the superconducting wiggler beamline X17C at NSLS, or in angle using focused monochromatic x-rays from the wiggler beamline 10-2 at SSRL. **Figure 2** shows a typical energy-dispersive x-ray diffraction pattern for osmium at 65 gigapascals, consisting of the diffraction lines from hexagonal close packed osmium and face-centered cubic argon, and the x-ray emission lines from osmium.

Measured compression data for osmium, iridium, and ruthenium were fit using the third-order Birch-Murnaghan equation of state (EOS). The osmium data and fit are both shown in **Figure 3**. We have also carried out first-principles calculations of the EOS for these three metals. The calculations yield the same trend in the bulk moduli, thus providing an independent confirmation of our experimental results.

In summary, we found that osmium has the largest bulk modulus yet measured. This result provides impetus for a continued search for superhard materials, including transition metal carbides, nitrides, borides, and oxides.

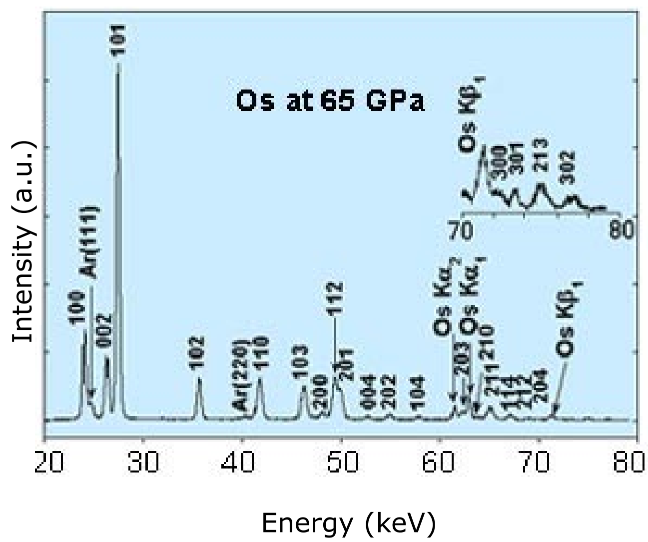


Figure 2. Energy-dispersive x-ray diffraction pattern (EDX) of osmium at 65 gigapascals. Inset shows expanded view from 70 to 80 keV. The EDX were measured at the X17C beamline of NSLS, using unfocused white x-rays from the superconducting wiggler beam.

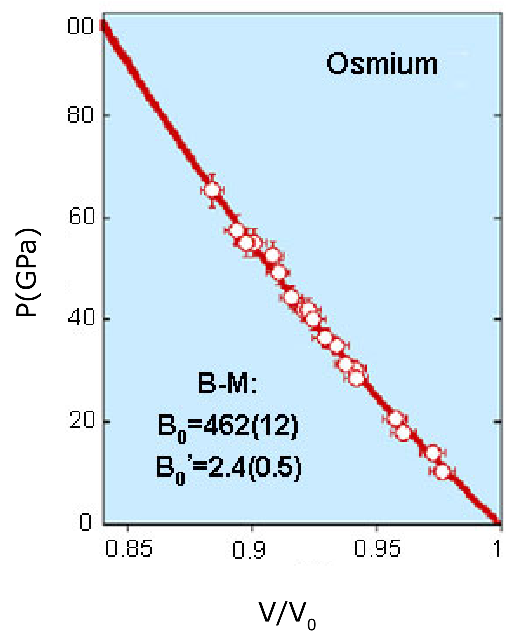


Figure 3. Volume compression data for osmium, fit with the Birch-Murnaghan equation of state, yielding the bulk modulus B_0 and its first pressure derivative of B_0'.